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ANALYSIS OF NEAR-FIELD THERMAL-HYDROLOGICAL BEHAVIOR FOR ALTERNATIVE REPOSITORY DESIGNS AT YUCCA MOUNTAIN

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Three-dimensional calculations are required to adequately represent drift-scale thermal-hydrological behavior that will result from the emplacement of waste packages (WPs) in the potential high-level waste facility at Yucca Mountain. To carry out such calculations, a three-dimensional, drift-scale, multiple-WP model, based on the NUFT code[1], was developed. This is the first published thermal-hydrological model that discretely represents a mixture of WPs with different heating histories.

Calculations were carried out to compare two repository designs: the Advanced Conceptual Design[2] (called the ACD) and the line-load design (also called Localized Dryout concept)[3]. The focus of the study was to examine differences between the two designs (both with and without the use of backfill) with respect to temperature *T* and relative humidity *RH* experienced by WPs. These quantities strongly affect WP integrity.

A mixture of WP types was studied, ranging from those containing very hot spent nuclear fuel (SNF) to virtually cold defense high-level waste (DHLW). The model includes six major WP types, resulting in a WP inventory that is representative of that assumed for the ACD[2], including four SNF WP types: (1) "very hot" 10-yr-old "design basis fuel" PWR WPs (comprising 10% of the WPs in the model), (2) "relatively cool" 40-yr-old PWR WPs (10% of the WPs), (3) nominal 26-yr-old PWR WPs (20% of the WPs), and (4) nominal 26-yr-old BWR WPs (20% of the WPs), and two types of DHLW, including those from the Hanford site (10% of the WPs) and those from the Savannah River site (20% of the WPs). The drift diameter is assumed to be 5.5 m; however, drift diameters of 3, 4, and 6.5 m were also analyzed. A sensitivity study of thermal radiation in the drift considered WP emissivities ranging from 0.3–0.8. For the backfill cases, a sand backfill was assumed; backfill thermal conductivity K_{th} = 0.3 and 0.6 W / m°C were considered. For the line-load backfill cases, it is assumed that measures are taken to prevent backfill from filling the gap separating WPs; line-load cases were also considered where backfill is allowed to fill in between WPs. In addition to the reference areal mass loading (AML = 84.3 MTU/acre), AMLs of 25, 45, and 100 MTU/acre were also considered. Ambient percolation fluxes ranging from 0–5 mm / yr were considered.

There are two different ways that WPs can be arranged in the repository at Yucca Mountain. The ACD utilizes a "square" geometry with the spacing between drift centerlines being roughly the same as the axial center-to-center spacing between SNF WPs. The ACD has a lineal mass loading LML = 0.46 MTU/m of drift. The line-load design places WPs nearly end-to-end (this study assumed a 10-cm gap between WPs, resulting in LML = 1.11 MTU/m); to keep the areal mass loadings the same (83.4 MTU / acre) in the two designs, the drift spacing in the line-load design is 2.4 times greater than in the ACD (see Table I).

The axial WP spacing in the ACD is large enough to thermally isolate the WPs from one another (particularly if backfill is used), so that some WPs will be very hot and dry, while others will be cooler and much more humid (Table I). The close axial WP spacing in the line-load design results in highly efficient WP-to-WP heat transfer, so that, in spite of their different heating histories, all WPs experience similar (and beneficial) *T* and *RH* conditions. During the pre-closure period (t < 100 yr) as well as during the post-closure period for cases without backfill, the coolest and most humid WP in the line-load design has a lower *RH* than the hottest and least humid WP in the ACD (Table I). The higher LML in the line-load design results in more locally intensive (and uniform) rock dryout around the drifts and the larger drift spacing allows for more effective condensate shedding between the drifts, thereby facilitating less condensate buildup above the line-load drifts. For percolation fluxes of 0.3 mm / yr or greater, the LML in the ACD is not insufficient to partially dry out, even for a limited period of time, all portions of the rock adjacent to the drift walls; consequently, humid ambient conditions always prevail along the portions of the drifts containing the cooler WPs. Moreover, the wet portions of the ACD drifts experience heat-pipe conditions at the upper drift wall, resulting in condensate flux into the drift.

The last two rows of Table I list the time required to rewet to RH = 65 and 90%; these RH thresholds are listed because corrosion studies of the candidate WP materials indicate that the critical RH for atmospheric corrosion to be 65% if an evaporitic salt is present on the WP or 90% if the WP surface is free of salt. For the cases without backfill, the line-load design significantly extends the time required to reach these RH thresholds (relative to the ACD). When backfill is used, the time to reach these RH thresholds is substantially increased for all WPs in the line-load design, while for the ACD, it is only substantially increased for the SNF WPs (with DHLW not benefiting from RH reduction). The additional reduction in RH for the backfill cases arises from the large (and persistent) temperature difference between the WP and drift wall (called $\Delta T_{\text{drift.}}$)[3]. This effect (the "drift-ΔRH effect") occurs in addition to any reduction in RH resulting from rock dryout (ΔRH_{rock}). Assuming uniform P_v in the drift, RH on the WP is given by

$$RH_{\text{wp}} = RH_{\text{dw}} \frac{P_{\text{sat}}\left(T_{\text{dw}}\right)}{P_{\text{sat}}\left(T_{\text{wp}}\right)}, \tag{1}$$

where RH_{dw} is RH in the rock at the drift wall, T_{dw} and T_{wp} are the drift wall and WP temperatures. When a lower backfill K_{th} is used, $\Delta T_{\text{drift.}}$ is larger, resulting in a larger and more persistent reduction in RH (compare the last two columns of Table I).

The line-load design may provide the following benefits: (1) a substantial reduction (up to 58%) in the required total length (and number) of emplacement drifts (relative to the ACD) with a corresponding cost reduction; (2) a substantial reduction in material required to backfill the drifts; (3) a substantial reduction in the range of T and RH for which natural and engineered materials must be tested; (4) much less spatially variable thermal-hydrological behavior in the near field that must be accounted for in performance analyses, and (5) beneficial RH reduction for all WPs (including DHLW).

Table I. Temperature and relative humidity on WPs for AML = 83 MTU/acre, WP emissivity = 0.8, and percolation flux = 0.3 mm/yr.

Repository design	**ACD rev 00**	**ACD rev 00**	**Line load**	**Line load**	**Line load**
LML	0.46 MTU / m	0.46 MTU / m	1.11 MTU / m	1.11 MTU / m	1.11 MTU / m
Drift spacing	22.5 m	22.5 m	53.8 m	53.8 m	53.8 m
Backfill K_{th}	no backfill	0.6 W / m°C	no backfill	0.6 W / m°C	0.3 W / m°C
T_{peak} (t < 100 yr)	107–192°C	107–192°C	172–203°C	172–203°C	175–206°C
$RH_{\max}$ (t < 100 yr)	25–86%	25–86%	16–21%	16–21%	16–20%
T_{peak} (t > 100 yr)	104–144°C	117–353°C	147–158°C	250–266°C	352–362°C
RH (t = 120 yr)	29–85%	1–57%	18–23%	2–3%	1–1%
RH (t = 2000 yr)	86–97%	43–98%	72–75%	49–51%	35–36%
RH (t = 10,000 yr)	92–99.9%	60–99.7%	94–97%	73–77%	58–61%
t(RH = 65%)	0–630 yr	160-13,330 yr	1450–1620 yr	3730–4600 yr	12,700-15,560 yr
t(RH = 90%)	1170–2330 yr	950–62,680 yr	4030–4680 yr	30,480-39,820 yr	55,030-70,220 yr

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